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Microcircuit Trace Cutting with Focused Ion Beams

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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When a failed microelectronic device is examined in a scanning electron microscope (SEM), several possible failure sites are often visible, but positive identification of the primary failure site based on micrographs alone is difficult. Several other SEM imaging modes--e.g. electron beam induced current (EBIC) and voltage contrast imaging--have been shown to be very helpful in identifying failure sites or clarifying failure mechanisms. These methods involve collecting current or supplying voltage signals through external leads to the failed device. However, application of these techniques is precluded if shorting of device elements (traces) has occurred as a result of castastrophic failure. Failure analysis is facilitated if trace metallizations can be cut selectively to isolate the electrically shorted portions of the device. This report describes the disadvantages of current trace cutting techniques and introduces a new method without these disadvantages - focused ion beam cutting.

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PREFACE

The authors gratefully acknowledge the assistance of N. Marquez in the work covered by the report.

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1. INTRODUCTION

When a failed microelectronic device is examined in a scanning electron microscope (SEM), several possible failure sites are often visible. Positive identification of the primary failure site, based on secondary electron micrographs alone, is difficult. Several other SEM imaging modes--e.g., electron beam induced current (EBIC) and voltage contrast imaging--have been shown to be very helpful in identifying failure sites and clarifying failure mechanisms. These methods involve collecting current or supplying voltage signals through external leads connected to the specimen. Unfortunately, the application of these techniques is precluded if, as is often the case, shorting of device elements (traces) occurs as a result of catastrophic failure. Failure analysis is facilitated if trace metallizations can be cut selectively to isolate the electrically shorted portions of the device. By clearing of a short, failure sites can be identified. Measurements of circuit parameters of the remaining part of a device are also made possible, and may provide information about the degradation mechanism. In addition, the removal of electrical shorts by trace cutting permits the application of techniques such as EBIC to portions of a device where degradation may have occurred but where the "evidence" has not been obscured by catastrophic failure. Metallization widths in many microelectronic circuits are in the 1 μm range; cutting techniques that can provide high spatial resolution are essential. Each method currently employed for trace cutting has certain advantages and limitations. We report here on the use of a focused ion beam from an ion microprobe for precision trace cutting. This cutting technique offers high spatial resolution and the opportunity of incorporating a sensitive method for end-point detection.

Trace-cutting techniques now in use include mechanical cutting with fine probes, chemical etching, and laser cutting. Mechanical cutting is a simple technique that requires only a microscope and a micromanipulator with a probe that has a sharp edge. However, probes small enough to afford good spatial resolution are difficult to manipulate. An additional complication is that

soft metals, such as gold, simply smear when contacted by a mechanical probe and it is very difficult to break the conducting path completely. Chemical etching is difficult to apply selectively to narrow traces. Surface tension effects are important with small drops, and liquid tends to flow where it is not wanted. The necessity for removal of etchant after use further complicates the procedure.

Laser-trace cutting is the technique most directly comparable with ion beam cutting.[1] Laser cutting is a thermal ablative process in which material is removed from the target by a series of pulses from a zenon or YAG laser. The minimum apparent size of the crater made by a laser cutter depends on the thickness of the metal being cut, but seems typically to be around 2 μm. Certain features inherent to laser cutting make control of the process difficult. Light absorption, for example, varies among materials. On a passivated trace, laser light penetrates the oxide and is absorbed by the metal underneath to produce a small "explosion." Cuts made by ablation are often surrounded by debris, which can immensely complicate subsequent steps necessary in the analysis. In addition, compound semiconductors, such as gallium arsenide, decompose at the temperatures generated by laser cutting and on these materials the substrate beneath the target metal can be damaged.

Focused ion beam cutting can be accomplished by use of an ion microprobe designed primarily for elemental analysis. The incident ions sputter material from the specimen as gaseous ionic or molecular species, leaving little or no residue. Sputtered species are analyzed by a mass spectrometer to provide a chemical analysis of the specimen; in fact, mass analysis provides a convenient way of determining when a metallization has been severed. We have found that the trace-cutting capability of the ion probe, in combination with its capability for elemental analysis, makes it an especially useful instrument for the analysis of electronic devices.

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[1] R. L. Waters and J. K. Logan, "Methods of Trace Cutting for Diagnostic Probing of Semiconductor Devices," Proc. 1984 International Symposium for Failure Analysis, Los Angeles, CA.

2. EXPERIMENTAL

The ion probe in our laboratory was manufactured by Applied Research Laboratories. Ions can be focused to a spot with a minimum diameter of about 2 μm to provide elemental analyses with high spatial resolution. In addition to producing a small circular spot, the beam can be rastered along a line or over a rectangular area. The size and shape of a cut can thus be chosen with considerable freedom. The ion beam was positioned on the test circuit by a 200× optical microscope, and the specimen was observed during the sputtering. Sputtering was continued until a trace appeared to have been severed, as evidenced first by the appearance of a metallic luster as overlying glassivation was removed, followed by the apparent disappearance of metal. The beam diameter was 2 μm, the ion energy 20 keV, and the beam current was 0.5 nA. A commercial microwave power gallium arsenide field-effect transistor (GaAs FET) was employed as a test device in this study (Fig. 1). An FET is essentially a voltage controlled resistor which consists of a semiconducting channel connected to ohmic (source and drain) contacts at each end. The current flowing through the conducting channel is controlled by a voltage applied to a Schottky contact (the gate) placed between the drain and the source, and the gate is reverse biased in normal operation so that the input impedance is high. Two cuts were required to isolate a segment of the gate circuit because of a "wrap-around" gate geometry, and each required a sputtering time of about 5 minutes.

The electrical isolation of traces by ion cutting is demonstrated by use of the EBIC imaging mode in a scanning electron microscope (SEM). When an incident electron beam impinges on the gate of an FET, the electron-hole pairs generated by the beam are separated by the electric field intrinsic to the Schottky junction between the overlying gate metallization and the GaAs. The gate Schottky barrier acts as a solid-state electron multiplier. As the SEM beam rasters across the device, an EBIC image is formed by use of the current collected from the gate lead of the FET (with drain and source leads grounded) as the SEM display input. The regions of the gate that have both a functioning Schottky barrier and are electrically connected to the external gate lead appear bright in an EBIC micrograph.

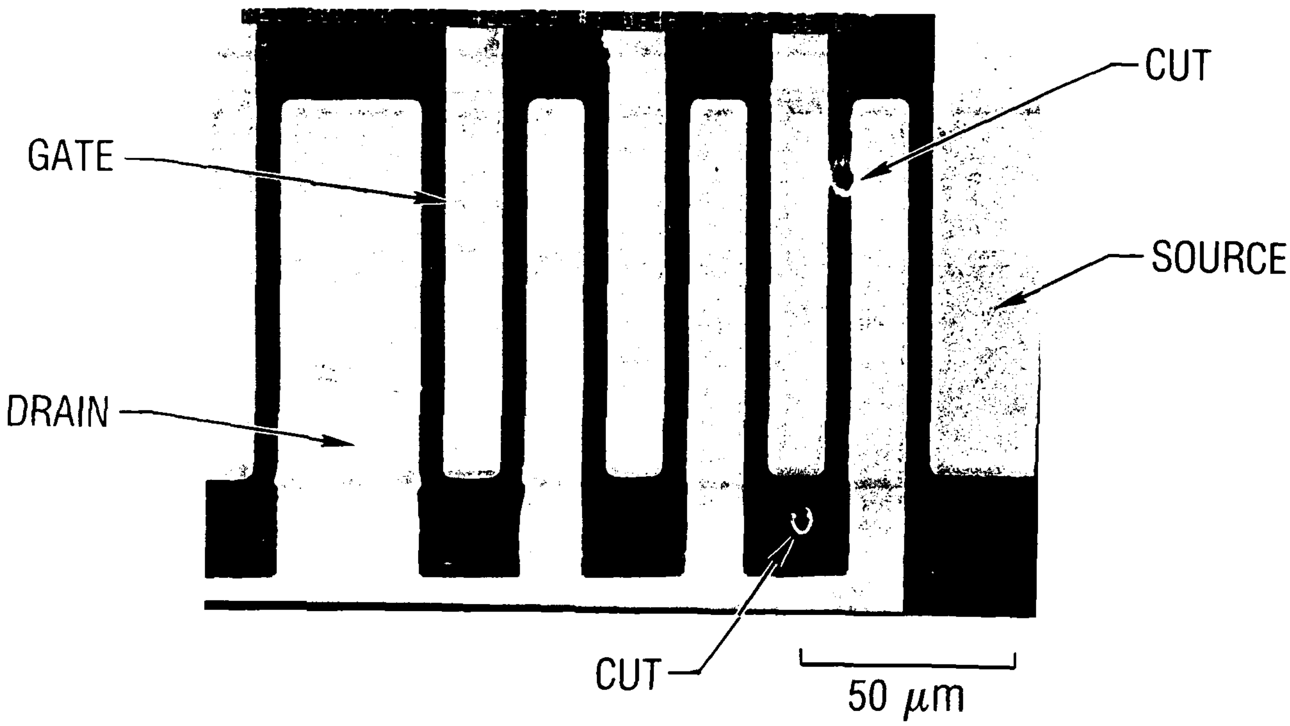

Fig. 1. Secondary Electron Micrograph Showing General Structure of GaAs FET. Circular features are trace cuts made by ion beam.

3. RESULTS AND DISCUSSION

The connectivity of the gate metallization is shown by the EBIC picture of Fig. 2, taken before trace cutting. There are no gaps in the gate metallization, which appears as a bright pattern. A region of the gate was selected for isolation by ion trace cutting. The EBIC micrograph obtained after ion trace cutting (Fig. 3) clearly shows that the section of the gate between the ion beam cuts has been electrically isolated. Ion cutting did not leave much debris. The cuts are clean and well defined (Fig. 4).

Although the mass spectrum peaks from the metallization or substrate can in general be used as "end-point" detectors to minimize the amount of cutting needed, the spectrometer output was not monitored during trace cutting in this particular test case because of an unfavorable geometry of the device and our ion microprobe. The FET chip is at the bottom of a relatively narrow and deep package which interfered with postioning of the mass spectrometer pickup electrode.

A number of mechanisms can be involved in the degradation of GaAs FETs, including electromigration in both drain and source and gate metallizations, as well as electromigration across the channel. RF and DC characteristics may exhibit gradual degradation with some retention of function, but failure is often catastrophic. Traces melt, and the gate is usually shorted to the drain and source. If damage is not too excessive, shorted portions of the gate may be isolated by trace cutting. EBIC imaging can then provide information about the integrity of the remaining portions of the gate metallization, which can help in identifying the degradation mechanism.

Trace cutting with focused ion beams has other potential microelectronic applications besides failure analysis. One such application is the isolation of defective or redundant sections of circuits to improve yield as individual devices on a wafer become larger and more complex.

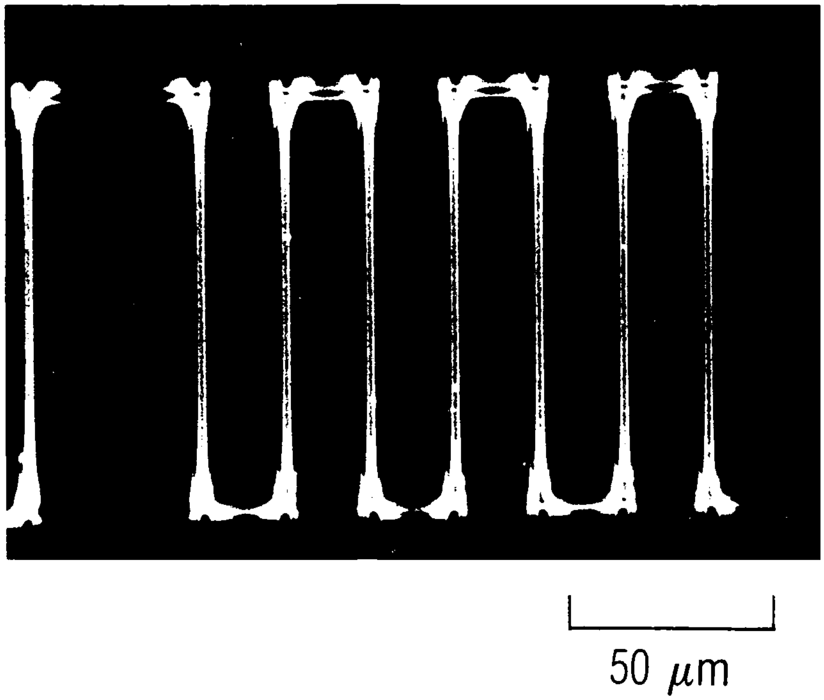

Fig. 2. Electron Beam Induced Current (EBIC) Micrograph Showing Initial Electrical Connectivity of Gate Metallization

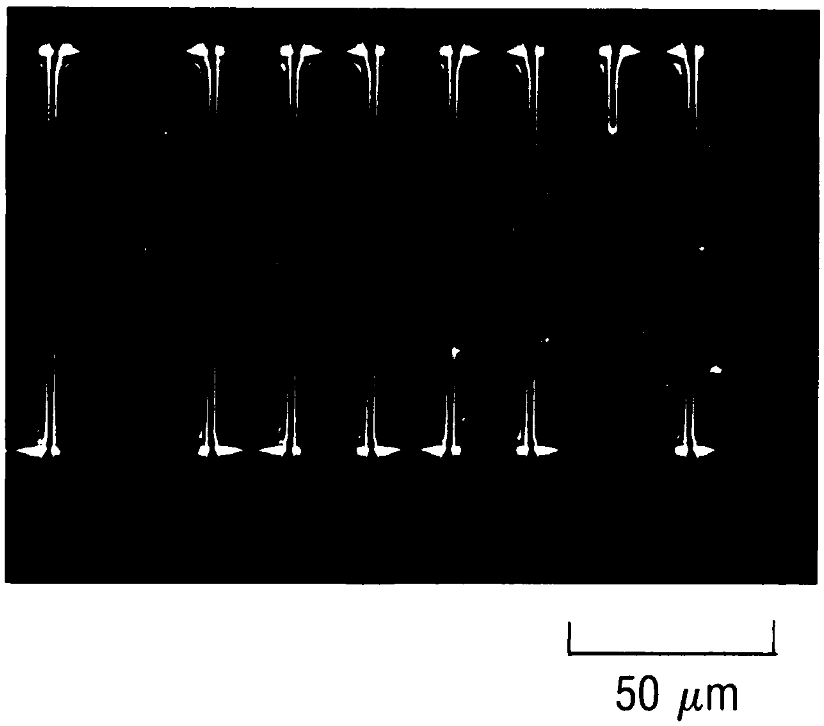

Fig. 3. EBIC Micrograph After Ion Trace Cutting, Proving Electrical Isolation of Target Portion of Gate

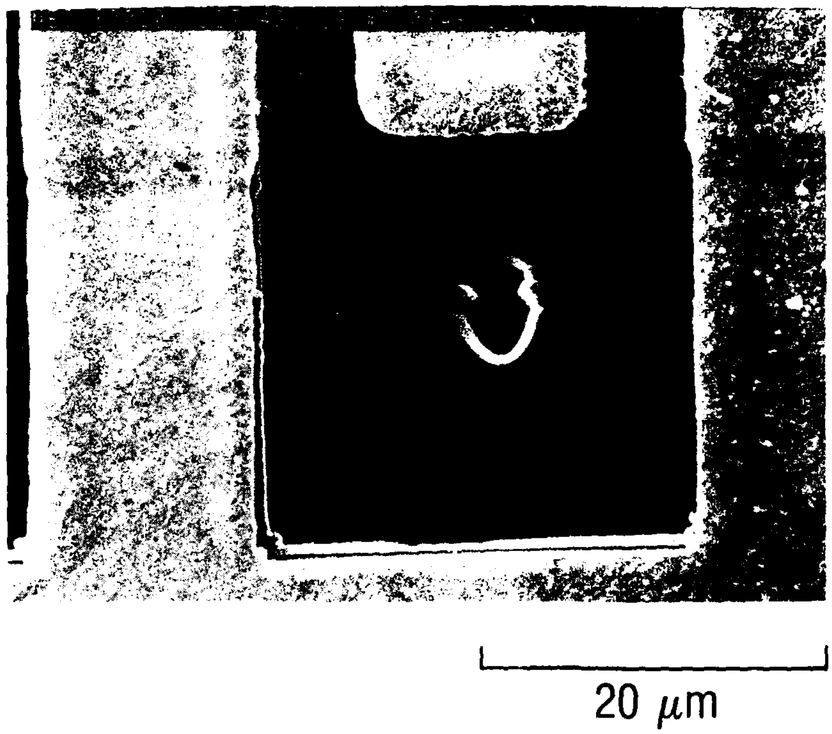

Fig. 4. Secondary Electron Micrograph Showing Ion Cut in More Detail

CONCLUSION

In addition to providing elemental analyses with high spatial resolution, we have shown that an ion microprobe is a valuable tool for precision trace cutting in microcircuits. Trace cutting helps provide positive identification of failure sites and helps resolve ambiguities which may arise when several possible failure sites are found.